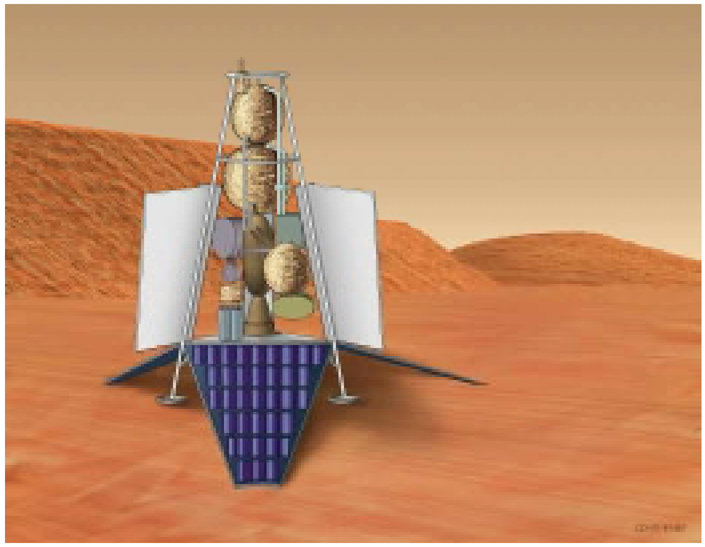
In-situ-refueled Rocket "Hopper" for Mars Exploration



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Summary:

A reusable rocket-powered "hopper" vehicle explores the Martian surface under rocket power and can repeatedly takeoff and land, carrying a suite of science instruments over a range of hundreds of meters per hop. The flight demonstration will accomplish a range of technology objectives critical to future human missions, and will be a science platform that complements ground and orbital observations.

The science goal is to provide a platform for science with superior mobility across the surface of Mars. The baseline list of science payloads for the vehicle includes:

- ***Close-range aerial photography.***

The aerial view of the landing site will be invaluable for geomorphology and placing geological investigations in a proper context. We will get high-detail images at a different sun angle and from a different physical perspective than the images taken by the descent imager during landing. Stereo information will be derived from viewpoints taken from different positions. Our aerial images will complement the science data obtained from other means. To quote the philosopher Yogi Berra: "You can see a lot just by looking."

- ***Meteorology.***

Studies of Martian climate and meteorology will benefit greatly from an expanded range of altitudes for temperature and wind measurements.

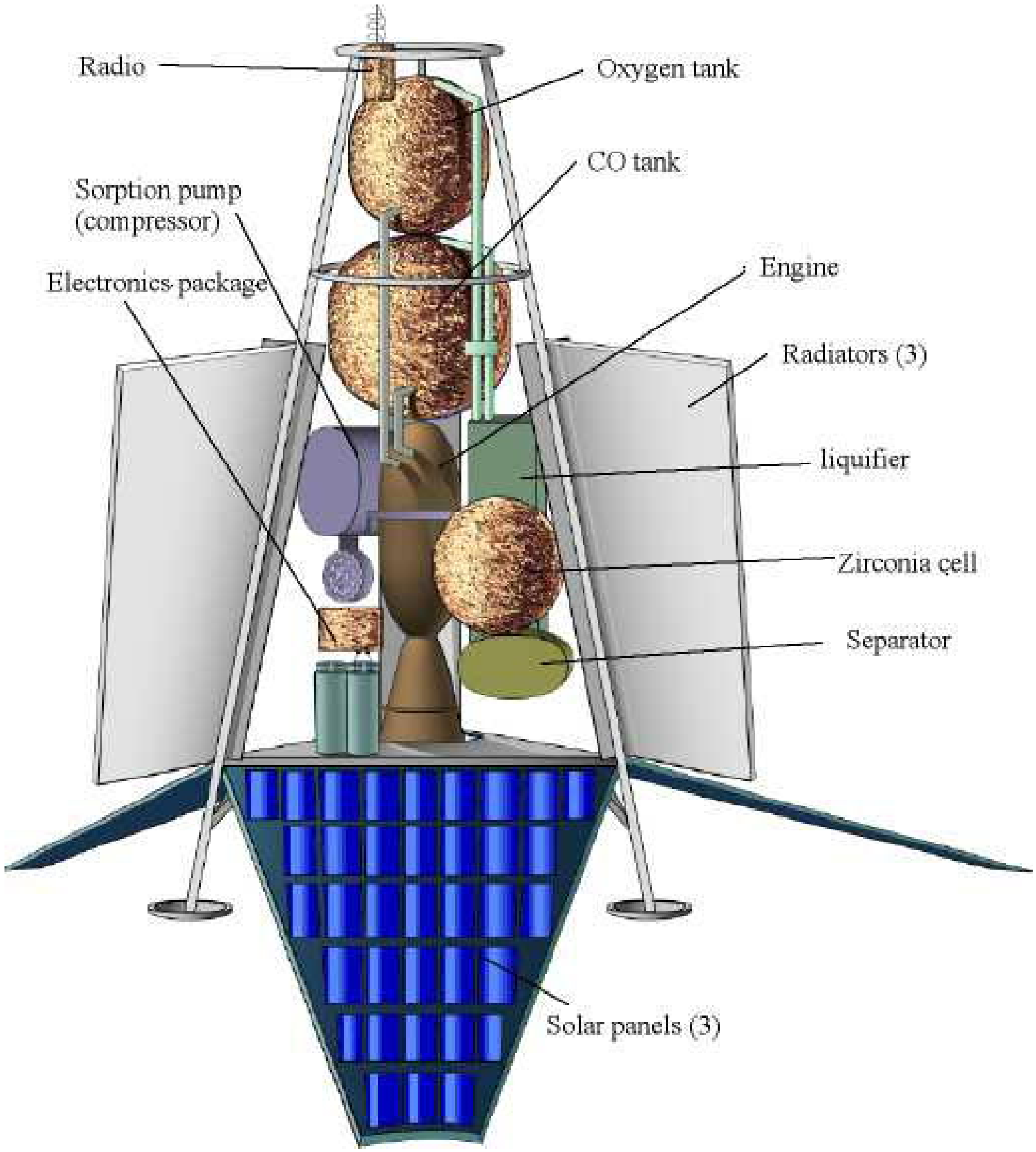
- ***Geological measurements at isolated remote sites.***

Since the vehicle easily traverses obstacles that rovers cannot, we will be able to sample regions that are geologically interesting but too rugged for surface rovers to reach. An suite of surface-measurement instruments will measure the properties of each landing site.

Technology goals and objectives

In addition, the vehicle addresses goals of Human exploration listed by the Mars Exploration Program payload analysis group.

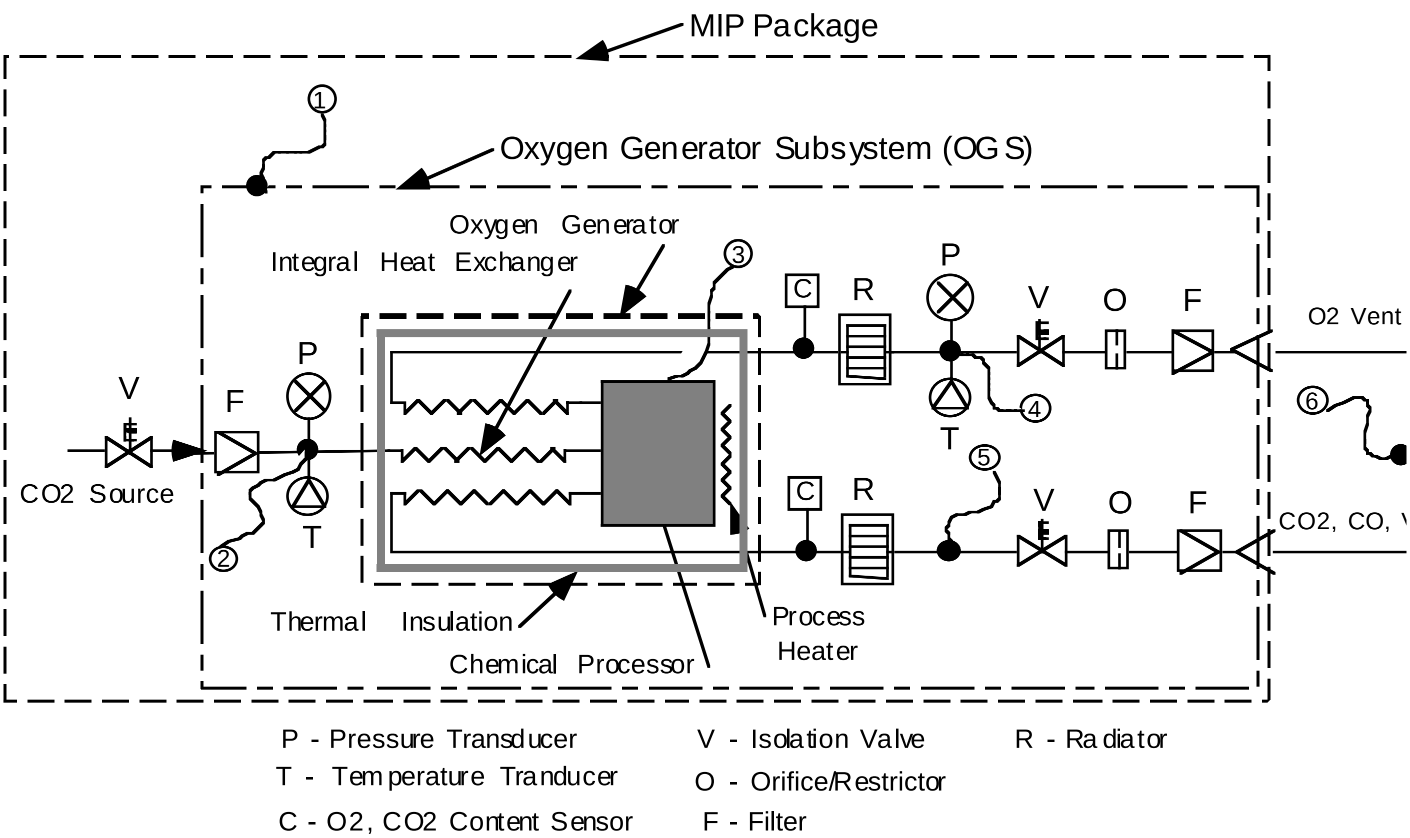
- **HEDS goal B-4**, in-situ propellant manufacture and utilization (high-priority task; this is mission-enabling for Human exploration).
- **HEDS goal A-4**, measure atmospheric parameters and variations that affect atmospheric flight
- **HEDS goal of demonstrating landing and LIDAR altimeter use**


Radio
Oxygen tank
CO tank
Sorption pump
(compressor)
Electronics package
Engine
Radiators (3)
liquifier
Zirconia cell
Separator
Solar panels (3)

Oxygen Generation System from MIP

Zirconia cell electrolysis

Basic electrolysis process: $2CO_2 \rightarrow O_2 + 2CO$



MIP is flight qualified hardware

Details are given in a paper to be published in *Journal of Spacecraft and Rockets, Vol. 23*, No. 4, 2001

An earlier version of this paper was presented as paper AIAA-2000-3120, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama, July 16-19 2000

ISRU Introduction and Background

A critical – and enabling – technology for the human exploration of the planet Mars is *in-situ propellant production* (ISPP). ISPP involves the manufacturing of propellants on Mars using indigenous resources as feedstock in the chemical processes. The primary resource on Mars available for ISPP is the atmosphere, which is 95% carbon dioxide (CO_2). This CO_2 can be converted directly into oxygen (O_2) and carbon monoxide (CO), or, with some hydrogen brought from Earth, into O_2 and methane (CH_4). These propellants fuel the crew's Mars ascent vehicle:

that propellant mass typically will be 60% to 80% of the vehicle mass. Analysis of a candidate human Mars mission shows a potential reduction of up to 30% in the Earth-launched mass if ISPP technology is utilized at Mars.

The importance of ISPP is recognized in the NASA Strategic Plan, which states: " The Space Science Enterprise missions will also demonstrate the feasibility of utilizing local resources to 'live off the land.' "

A demonstration of ISPP was scheduled for flight on the Mars Surveyor 2001 Lander, where one of the technology payloads was a demonstration of a small-scale oxygen production plant. The 2001 Surveyor lander mission was cancelled as a result of the program changes following the loss of the Mars Polar Lander and Mars Climate Observer, however, the flight hardware for this propellant demonstration was built and qualified.

The proposed MIPR vehicle will demonstrate the use of the ISPP technology in a small vehicle designed to fly on a Mars Surveyor class mission. It will also demonstrate a cryogenic propulsion system for Mars ascent vehicles, lightweight space engine technology, and other innovative technologies for both Mars and Earth-based missions.

Mars Hopper: a New Vehicle for Mobility on Mars

Mobility on Mars has a high science value. Invariably, wherever a lander may touch down, we will always want to know what is beyond the next ridge, on top of the nearby hill, or just over the horizon. The *Pathfinder* mission (July, 1997) convincingly demonstrated the value of mobility on a planetary surface, and even though the *Sojourner* rover crawled at less than half a meter per second, and wandered no more than a maximum of twelve meters from the lander, the scientific (and public outreach) value of the *Sojourner* rover was incalculable.

Today the concept of surface mobility of Mars is defined by the use of rovers. This challenges that assumption. Surface rovers are limited by terrain, and cannot explore many of the most interesting territory on Mars. If a vehicle were to rise above the surface, it could traverse “impassible” chasms and hop over “uncrossable” cliffs.

A valuable surface explorer would be a "hopper" vehicle able to take off and land repeatedly, carrying a suite of science instruments over hundreds of meters per hop. The rocket-powered hopper is designed to achieve the following objectives:

- • refuels itself autonomously for multiple hops by using solar power to react atmospheric CO_2 into oxidizer and fuel;
- • achieves an altitude of several hundreds of meters and traverses a distance of several hundreds of meters during each hop; and

• carries a suite of scientific instruments to a soft landing at the conclusion of each hop.

Description of Mission

In-situ production of methane-oxygen propellant via the "Sabatier" reaction has been proposed for Mars sample return missions and for human Mars exploration. However, methane-oxygen propellant production requires hydrogen, typically from Earth. Use of a consumable for propellant production will limit the range of a hopper vehicle. For a hopper vehicle without such a limitation, we chose the carbon monoxide/oxygen (CO/O_2) propellant combination, produced by zirconia electrolysis. Because of its low specific impulse (~250 seconds), CO/O_2 is impractical as a propellant for an Earth return vehicle for a sample return mission (although it may be usable for the first stage of such a vehicle, where performance is largely insensitive to specific impulse). For the hopper vehicle proposed, however, since this propellant requires no consumable hydrogen for production, CO/O_2 is ideal .

The hopper will be situated on the science deck of a Surveyor-class Mars lander. Once the lander sets down on Mars, the solar arrays will begin to produce power to operate its propellant production plant. The available power will determine the production rate.

Our preliminary designs indicate that the production plant will be at least half of the hopper's dry mass. The distance achieved during a hop is a function of launch angle, quantity of propellants, thrust, and dry mass. For initial planning purposes, we have assumed a launch angle of 45 degrees to maximize range. As a technology goal, we want to demonstrate an engine large enough that it can be scaled up for a Mars sample-return mission where required thrust is expected to be 1700 to 2200 N (400 to 500 lbf). However, it is also important to keep hopper thrust levels low, to minimize mass and to allow a soft landing after each hop. For this mission, we anticipate engine thrust to be 200 to 700 N (50 to 150 lbf). An engine thrust of 335 N (75 lbf) was used for calculations in this paper.

The nature of the hop is determined by the dry mass of the vehicle, the O_2 and CO production rates (measured in standard cubic centimeters per minute (sccm)), and the length of time between hops.

For the example flight profiles, the dry mass of the vehicle was held constant at 18.9 kg. Flight duration varies from 32 seconds for the 500-m hop to 48 seconds for the 4000-m hop. The longer hops need a larger amount of propellant, and hence require a longer time between flights to produce propellant. The propellant production time ranges from 50 days for the 500 meter hop to 155 days for a 4-km hop.

A 500-m flight was chosen for the design, using the assumption that more frequent hops (and hence a larger number of surface sites visited) were of higher science value than longer travel distance.

The required propellant mass and time between hops varies for a 500 meter flight for the various values of initial (launch) mass. The same 335-N engine was assumed for all profiles; the lighter vehicle actually achieves a slightly higher maximum altitude. Flight duration varies between 32 seconds for the 20 kg vehicle to 27 seconds for the 35 kg vehicle.

With a smaller initial mass, the production plant is smaller, and has a lower fuel production rate. This results in a longer wait between hops. To determine the time between hops, the mass of the propellants, tanks, science, engine, power system, cables, and structure are subtracted from the initial mass. The remaining mass is that which is available for the production plant, which in turn determines the production rate. The time between hops is 50 days for the lightest (20 kg initial mass) vehicle, and decreases as the vehicle size increases, reaching 28 days for an initial mass of 35 kg.

An example of the mass allocations is shown in table 1 for a 30.5 kg initial mass vehicle.

Aerial photographs, first from the lander and then from previous hops, will help determine a direction for each hop. This will allow the vehicle to be directed toward and over interesting scientific sites and to target a relatively benign landing site.

Table 1: Mars In-Situ Propellant Ballistic Hopper

Single Hop Range:	0.50 kilometers
Maximum altitude:	350 m
Engine Thrust:	335 N (75 lbf)
Engine Specific Impulse:	250 sec
Propellants:	Oxygen/ Carbon Monoxide
Duration between Hops:	31 days

Mass Summary

Component	Mass (kg)	Subsystem Mass (kg)	Comments
Ox. Tank	0.76		2000 psi storage, 15.7 cm diam.
CO Tank	1.72		2000 psi storage, 20.7 cm diam.
Subtotal for tanks		*2.48*	all metal or composite wrapped metal tanks; mass est. from Arde
Science		1	pressure, temps, wind for meteorology; aerial photos
Engine		3	pressure fed; based on existing engines
Solar arrays	0.25		20 W for 8 hrs daytime; ~1 m^2 at operating average specific power of 80 W/kg
Solar array structure	0.25		Assumed equal to solar array mass
Batteries	0.5		Lithium-ion; 24 W-hrs at 100 W-hrs/kg assuming 50% depth of discharge
electronics package	1		
Subtotal for power		*2*	
Propellant Production		18.4	Based on scale-up of MIP project (production rate = 30 sccm)
GNC	0.5		
Cables		0.29	1% of dry mass
Oxygen	0.49		
Carbon monoxide	0.89		
Subtotal for propellants		*1.38*	
Structure		1.52	5% of wet mass